Punctual Thermal Study of the Water Column on the Continental Shelf in the North Part of Yucatan

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Abstract

Three time series (March 11-21, May 19-June 5, and September 23-october 5) gathered in 1988 between Alacran Reef and Puerto Progreso, in the Yucatan peninsula, Mexico (22° 11'N y 89° 41'W) were used to elucidate the thermal assay of the water column carried out. The temperatures are measured every 3 h, in five levels (surface, 10, 20, 30 and 40 m depth). The surface heating velocities were -0.12, 0.07 and 0.03°C d^{-1}, respectively for each sampling period. During the first series a typical winter profile was observed, without a marked thermocline. The thicknesses of the mixed layers were determined from the temperature profiles; these were 40, 29 and 27 m, respectively. During the second and third sampling periods a thinning of the mixed layer was observed. The results of the heat storage computated through a parameterization of the mixed layer, underlayer and thermocline are presented and compared. The heat storage for each time series was -260, 48.5 and -3 W m^{-2}, respectively. Comparison of results with sea surface climatic patterns showed good agreement, not so the heating speed, whose differences were probably due to severe meteorological processes and to spatial-temporal scales of the results.

Resumen

A partir de tres series de tiempo obtenidas del 11 al 21 de marzo, del 19 de mayo al 5 de junio y del 23 de septiembre al 5 de octubre de 1988 entre el Arrecife Alacrán y Puerto Progreso, Yuc., México (22° 11'N y 89° 41'W), se realizó el estudio

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térmico de la columna de agua. Las temperaturas se midieron a los niveles de superficie, 10, 20, 30 y 40 m de profundidad, cada 3 h. Las velocidades de calentamiento superficial calculadas fueron -0.12, 0.07 y 0.03°C d^{-1}, respectivamente, para cada época de muestreo. Durante el primer muestreo no se observó la presencia de la termoclina, obteniéndose un perfil de temperatura típico de invierno. El tamaño medio de la capa de mezcla fue de 40, 29 y 27 m, respectivamente para cada época; en el segundo y tercer muestreo se observó un adelgazamiento de la capa de mezcla. Se presentan los cálculos del almacenamiento de calor utilizando una parametrización de la capa de mezcla, subcapa y termoclina y se realiza la comparación de resultados. El almacenamiento de calor durante cada muestreo fue de -260, 48.5 y -3 W m^{-2}, respectivamente. La comparación de los resultados con el patrón climático de la temperatura superficial del mar muestra cierta concordancia; sin embargo, las velocidades de calentamiento tienen diferencias que son atribuibles a procesos meteorológicos severos y a las diferentes escalas espacio-temporales de los resultados.

Introduction

The importance of the temperature in the ocean mixed layer has been widely discussed recently due to the consequences of ENSO (Lehodey *et al*., 1997) and global climate changes (Wang and McPhaden, 2000). That is why knowledge of the Sea Surface Temperature (SST), Mixed Layer Depth (MLD) and in general the thermal profile in the ocean, as well as the calculation of the contents and heat storage from historical and recent data, are very important (Alexander and Penland, 1996).

Few studies have been made related the heat storage and the ocean-atmosphere heat flow in the southern Gulf of Mexico and the Yucatan Channel, and lest in the Continental Shelf, where satellites have lower resolutions. The objective of this study is to show the behaviour of heat storage and ocean-atmosphere heat flow in one location of the continental shelf in the Yucatan Peninsula.

Levitus (1987) considered the heat content and heat storage of the ocean using a global scale. In the same way, Etter (1983) and Etter *et al*. (1987) did so for the Gulf of Mexico and the Caribbean Sea, respectively. Nevertheless, such information in shallow coastal regions is limited. In another context, Boudreau *et al*. (1992) found significant delays in the sinking of lobster postlarvae under the presence of an intense thermocline. However, the use of the thermocline as an internal boundary in numerical models has been questioned (Salmon, 1990).

Time series studies of temperature (Lagrangian sampling) reveal processes not before observed in the synoptic samplings (Eulerian sampling). These are enough to indicate the presence of a superadiabatic structure, with $\partial t / \partial z < 0$, z positive upwards (Anis and Moum, 1992, 1994). The separation of surface heating signals in turbulent heat flow and vertical advection also indicated the presence of a superadiabatic structure (Lee and Rudnick, 1996).

Adem *et al.* (1993) used a numerical model to estimate the seasonal climate cycle of heat balance on the surface water of the Gulf of Mexico obtaining a net incoming radiation of 210 W m^{-2} in July and 130 W m^{-2} in January; a latent heat flow of 100 W m^{-2} for July and 200 W m^{-2} in January; a sensible heat flow of 15 W m^{-2} in July and -30 W m^{-2} in January, and a heat storage of 80 W m^{-2} in July and -80 W m^{-2} in January.

The sampling point (22° 11'N and 89° 41'W), on the Continental Shelf of Yucatan Peninsula, Mexico (Figure 1) is located 22.3 km south of Isla Pérez. This location was chosen because it is the deepest zone of the channel between Puerto Progreso and the Alacran Reef, with a maximum depth of 50 m.

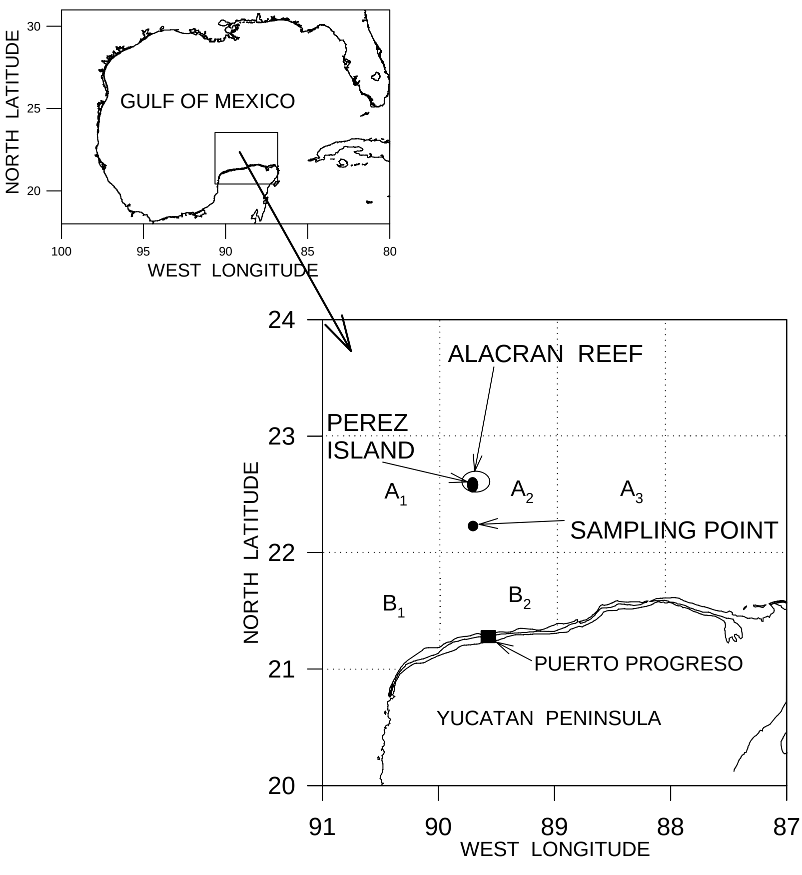

Figure 1. Location map of the study area, point of sampling and NOAA quadrants for the region (A1, A2 etc.).

The Continental Shelf of Yucatan, east coast of Mexico (Figure 1), is influenced by the Caribbean Surface Water (CSW), by the Yucatan Upwelling Water (YUW), and by the Gulf Common Water (GCW) (Merino, 1997).

The behaviour of the temperature on the region presents two strong signals, similar to monsoon. One during the winter owing to the passage of continental polar air masses coming from North America, locally called “Nortes”, and the other corresponds to trade winds during the rest of the year (Gutiérrez de Velasco and Winant, 1996).

The tropical cyclones that appear during summer and early fall produce modifications in the thermal structure of the ocean (Sakaida *et al.* 1998, Stramma and Cornillon, 1986). Hurricane Gilbert formed a tropical depression on September 8th, 1988 until it was upgraded to a tropical storm eastward of the Lesser Antilles on the 9th. It is estimated that Gilbert became a hurricane on the 10th. It made landfall on the Yucatan Peninsula on the 14th of September. The final landfall occurred late on the 16th as the centre moved toward the west of the Gulf of Mexico, crossing over the area studied. These maximum winds were 83 m s^{-1} and caused a reduction of the skin temperature (-0.69ºC d^{-1}) of up to 6°C to the right of its path (Jacob *et al.* 2000; Peabody and Amos, 1989).

Sea surface temperature is a critical quantity in the study of both the ocean and the atmosphere as it is directly related to and often dictates the exchanges of heat, momentum and gases between the ocean and the atmosphere. As the most widely observed variable in oceanography, SST is used in many different studies of the ocean and its coupling with the atmosphere (Emery *et al.* 1994, 1997, 2001, Ewing and McAlister, 1960). NOAA carries out climatic studies and have a database for more than 35 years, mainly with data obtained from satellites for quadrant of $1^o \times 1^o$. This SST climatic analysis is reported per month (NOAA, 1989).

This paper described the thermal characteristic of the water column, including SST and thermocline, at a point located between Puerto Progreso and Isla Pérez, Yucatan, Mexico, during three different periods in 1988. The calculated heat content and storage, and the results of the sea surface temperatures and surface heating speeds were compared against NOAA observed and climatic patterns.

Materials and Methods

Temperature data were recorded during three oceanographic cruises on 1988 (Aldeco and Aguilar-Sánchez, 1989). The first one was conducted from March 11th through 21st (11 days); the second one from May 19th through June 5th (18 days); and the third from September 23rd through october 5th (13 days), hereafter referred as S1, S2 and S3, respectively.

Hydrocasts were carried out every 3 h from an anchored vessel. The sampling were at surface, 10, 20, 30 and 40 m depth, using Niskin bottles on which 2 or 3 reversible thermometers (0.01ºC resolution) were adapted. The best fit straight line was used for each temperature time series obtained (one per level) in order to obtain the initial and final temperature by level, of each sampling period was recorded.

The temperature profiles were used to define the mixed layer depth. The 1°C criterion was used i.e., inferior limit of the mixed layer were considered where the temperature was equivalent to the sea surface temperature (SST) minus 1°C (Wagner, 1996). The heat content was first calculated only using the mixed layer depth (MLD), and then including the seasonal thermocline depth (sublayer) and the thermocline itself. Figure 2 sketches a profile of temperature, and the reservoirs used in the calculation of the heat content.

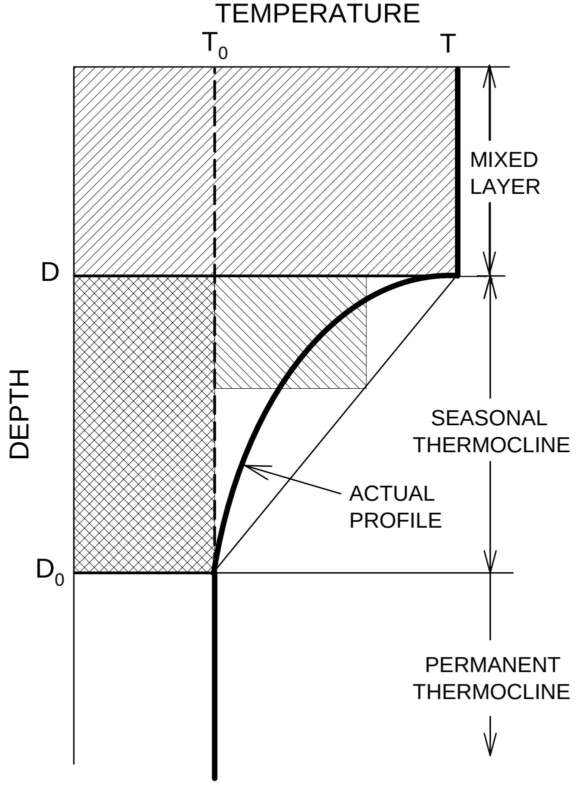

Figure 2. Schematic of temperature vs. depth profile showing a typical profile (heavy line), and areas used to calculate the heat stored in the column of depth D_0. From Meehl (1984).

Rates of heat storage in a layer of the ocean is defined as (Etter, 1983; Etter *et al*. 1987):

$$Q_t = Q(h,t) = \frac{d}{dt}\int_{-h}^{0} C_p \rho T(z) dz \quad (1)$$

Where $Q(h, t)$ represents the time variation of heat content (H) in a water layer of depth h and unit surface area; $T(z)$ is the temperature at depth z, ρ (1025 kg m^{-3}) and C_p (4187 J kg^{-1}°K^{-1}) are the density and the heat capacity of sea water, respectively.

The rate of heat storage in the water column, from the beginning of a sampling period to its end, is given by (Meehl, 1984):

$$\frac{dh}{dt} = \frac{(H_f - H_i)}{\Delta t} \quad (2)$$

Where H_i and H_f are the initial and final values of heat content in the sampling period, respectively. Δt is the duration of the sampling period. The heat content H is given by Meehl (1984) as:

$$H = [(TD) + T_0(D_0 - D) + C(T - T_0)(D_0 - D)]\rho C_p \quad (3)$$

Where T, D, T_0 and D_0 are defined in Figure 2. The first term in the right side of equation (3) represents the mixed layer, the second the subsurface layer and the third the thermocline. For the case of T_0, the minimum climatic SST minus 1.1°C (Robinson *et al*. 1979) was used, this is 21.5°C (NOAA, 1982-1988). For D_0 a value of 45 m was assigned. C_p is an area factor that depends on the slope of the thermocline and that was considered arbitrarily equal to 0.5. The error introduced by each tenth around this last value is 1% of H. For the calculation of the heat storage, the initial and final temperature values, for each level, were calculated from the straight lines of least squares fit, for each sampling period (Figure 3). The results obtained for heat storage from equation (3) were compared with latent and sensible heat flows obtained for S1 and S2 from Hernández-Téllez and Aldeco (1990).

Additionally, for the purpose of comparison between the methods, the heat storage was computed only taking into account the first term of equation (3); i.e., the final and initial SST's and the final and initial MLD's of each sampling period (Meehl, 1984):

$$\frac{\Delta H}{\Delta t} = \left[(T_f - T_i)\frac{(D_f + D_i)}{2}\right]\rho C_p \quad (4)$$

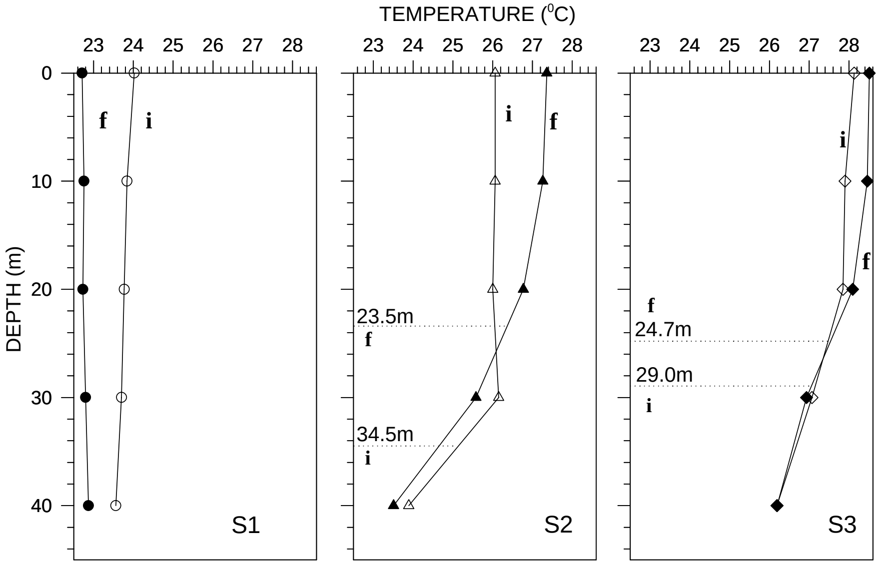

Figure 3. Initial (i) and final (f) temperature profiles of the sampling periods S1, S2 and S3. The numbers on the dotted lines are the MLD's used in the calculations of heat storage.

Finally, using 35 years of SST data obtained by NOAA (NOAA, 1982-1989, and —climatology of 29 years— NOAA, 1982) for quadrant A2 (1^{o} x 1^{o}; Figure 1), the climatic SST per month, and the observed SST per month during 1988 (NOAA, 1989), were obtained; and the heating speeds were computed ($\Delta SST / \Delta t$), where ΔSST is the change of sea surface temperature in a Δt time interval, a month. These values were compared with the observed and those computed from the sampling periods S1, S2 and S3, since other data are not available to compare the results.

Results

The temperature profiles from the beginning to the end of the sampling periods (Figure 3), showed an absolute maximum of 28.51°C at the end of S3 and a minimum of 22.71°C at the end of S1. During S1 (winter) the water column was homogenous, without a thermocline. At this time an average cooling of 1.0°C occurred.

During the period corresponding to S2 (summer) the water column was colder at the beginning of the sampling, down to a depth of 26 m. At greater depths the behavior is reversed and the temperature was cooler at the end of the sampling. The difference of the average temperature of the water column between the final and initial values, of the S2 sampling period was 0.79°C. During this sampling a thermocline could be observed (0.118ºC m^{-1}) approximately to a depth of 30 m, being stronger at the beginning of the period.

During the sampling period S3 (early fall) the highest temperatures appeared (average of 28.20ºC in the surface level), with a weak thermocline (0.083ºC m^{-1}) at a depth of approximately 27 m. The difference between the initial and final average temperatures of the water column was 0.15°C (the least of the three sampling periods). The upper layer down to 26 m being colder at the beginning of the sampling. Below 26 m the temperature pattern was reversed, in similar way to what happened during S2.

The mixed layer depth during S1 was the one corresponding to the whole water column, equivalent to 45 m. During S2 the observed initial depth of the mixed layer was 34.5 m and the final length was 23.5 m. For S3 at the beginning and end, the mixed layer depths were 29.0 and 24.7 m, respectively.

Figure 4 shows the temperature evolution of the time series at S3. S1 and S2 had interruptions and are not shown. The slope of the temperature time series (tendency), obtained at the indicated depths, displayed a very similar lift in the three upper levels of S3 (Figure 4). The behaviour at S2 was similar. For S1 negative slopes where observed at the five levels. For S2 and S3 the effect of the diurnal heating can be seen at the surface, which produces maximums every 24 hours. It was not so evident for S1. For S2 and S3, in the 10 and 20 m depth series, no significant oscillations were observed. Not so at depths of 30 and 40 m, where perturbations can be observed (Figure 4).

The average temperature of the water column during S1, S2 and S3 were of 23.30, 25.76 and 27.52°C, respectively. The temperature profiles, obtained by means of the temporary average by level for each one of the samplings periods (Figure 5), display a homogenous water column during S1; with a temperature difference between the averages from the surface and 40 m depth levels of only 0.17°C. During S2 the same difference between the upper and lowest level was 3.50°C, being the largest of the three sampling periods; whereas during S3 the difference was 2.19°C.

The rates of heating by level during each sampling period (Figure 6), present negative values (cooling) during S1, of -0.12°C d^{-1} at the surface and of -0.06°C d^{-1} at 40 m depth. During S2 it was observed that, at the surface level, the maximum rate of heating (0.07°C d^{-1}), below the 26 m depth the rate is negative, meaning cooling. S3 presents the lowest values of heating, 0.03°C d^{-1} at the surface, with a layer of cooling between the depths of 26 and 35 m (-0.01°C d^{-1}).

The heat storage calculated, using only the depth of the mixed layer (equation 4), first term of equation (3), yields values of -260, 104, and 39 W m^{-2} during S1, S2 and S3, respectively. The calculated rate of heat storage using equations (2) and (3) gave the following results: -260, 48.5 and -3 W m^{-2} during S1, S2 and S3, respectively, where the time interval corresponded to the duration of each sampling period; 11, 18 and 13 days respectively.

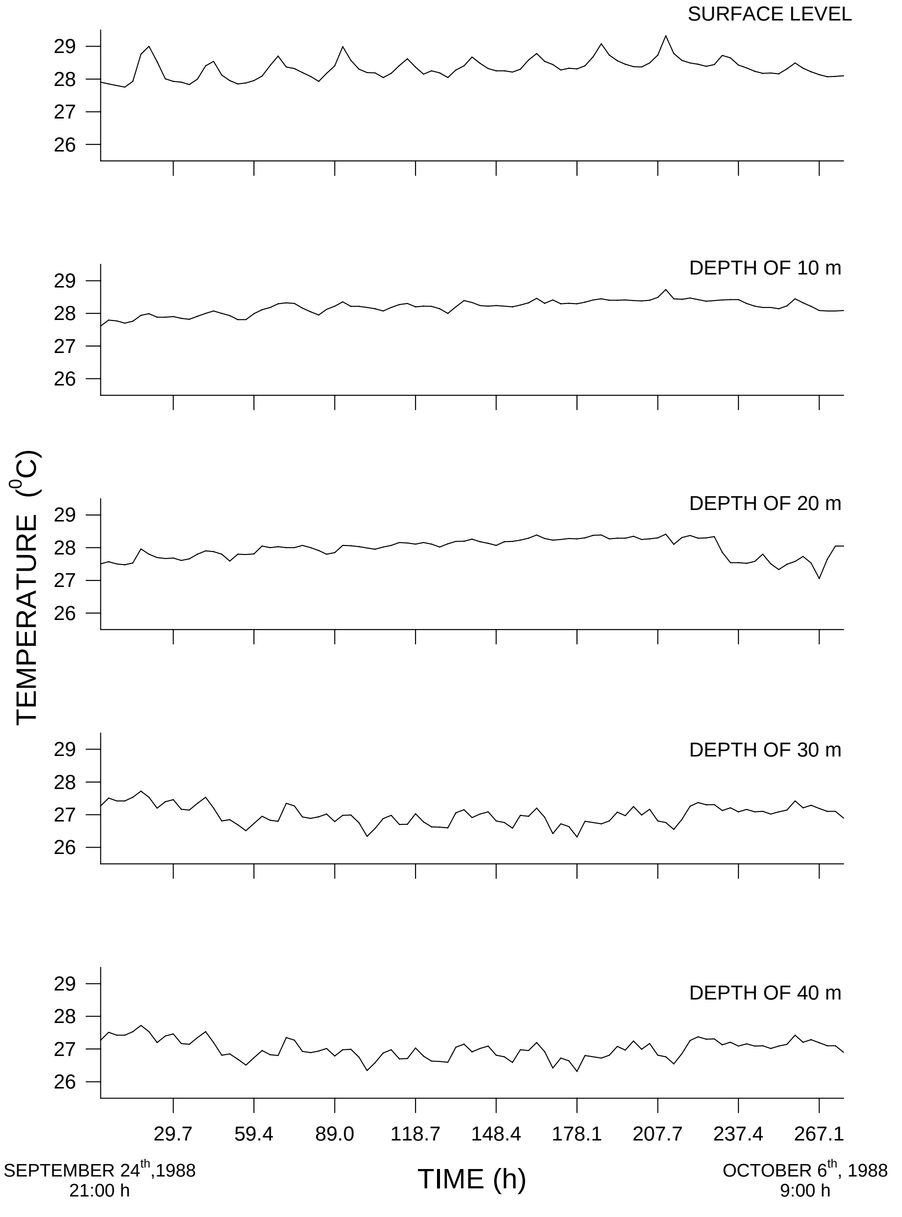

Figure 4. Temperature time series for the sampling period S3 by depth level.

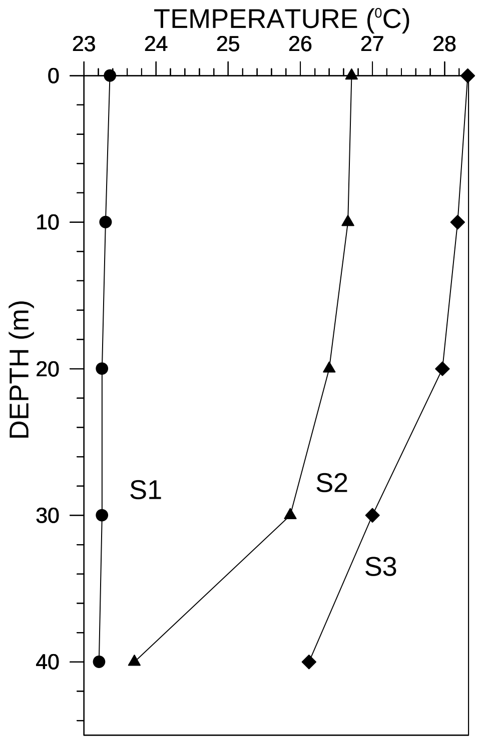

Figure 5. Average temperature profiles during the sampling periods S1, S2 and S3.

The time average of the sea surface temperature, as well as the rates of sea surface heating obtained in this study, were plotted along with the climatic values and the observations by the NOAA for the quadrant A2 (1^o x 1^o), where the station is located (Figures 7 and 8). In the first case it can be seen that the average surface temperatures during S1, S2 and S3 follow the general tendency of the climatic and the 1988 observed SST's, but not so the heating speeds.

Discussion

The dates for which the samplings were made represent late winter (S1), spring (S2) and early autumn (S3).

The initial and final temperature profiles of S1 are typically observed in winter, in this season an isothermal condition appears. The S2 profiles show a homogenous mixed surface layer and a cold intrusion of water into the inferior layer. During S3 it can be seen how the mixed layer increases its surface temperature, whereas probably a cold water intrusion below the depth of 30 m reduced the thickness of the mixed layer.

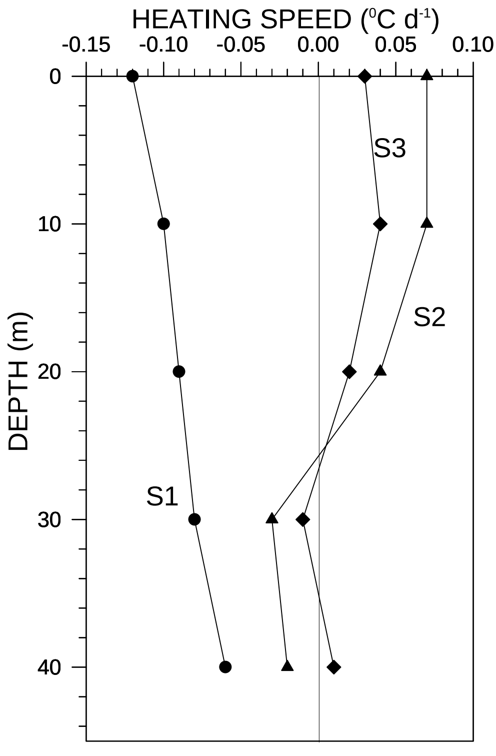

Figure 6. Heating speed profiles ($^{\circ}C\ d^{-1}$) during the sampling periods S1, S2 and S3.

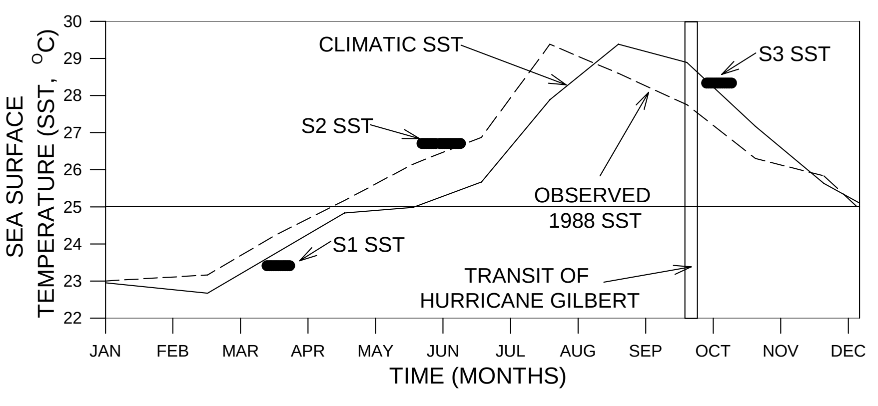

Figure 7. Average sea surface temperature, SST, during the sampling periods S1, S2 and S3 (heavy lines), climatic SST from NOAA data (continuous line) and observed 1988 SST (dashed line).

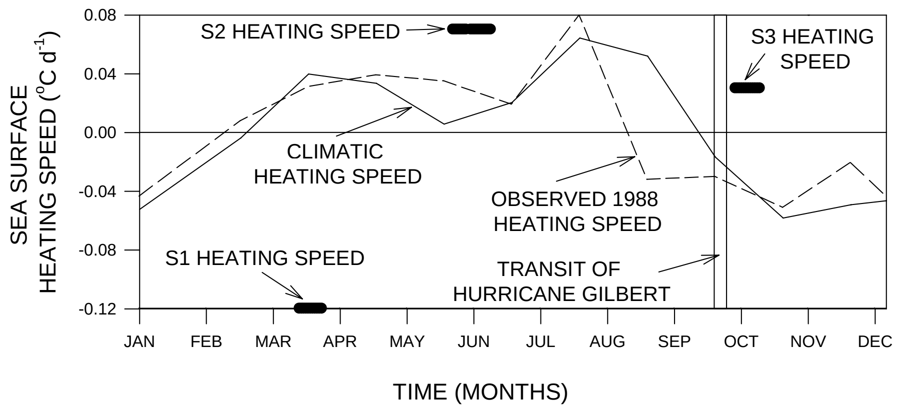

Figure 8. Sea surface heating speed during the sampling periods S1, S2 and S3 (heavy line), climatic sea surface heating speed (continuous line), and observed sea surface heating speed during 1988 (dashed line).

From the temperature series S3 it can be seen that the oscillations at the surface are not transmitted to the lower layers. There were smoothness at the levels of 10 and 20 m, and oscillations in those of 30 and 40 m, probably due to a cold water penetration at bottom. The behaviour of series S1 and S2 is in general similar (not shown). In S1 the oscillations are observed at the surface and during S2 oscillations at 30 and 40 m levels.

During S1 the negative rates of heating by level, with absolute values decreasing downward, suggests a heat flow from the water column towards the atmosphere. For S2 the thermocline migrated upward, and since the profile of the rate of heating indicates that above 26 m the water column gains heat and the layer under this level yields heat. The possible explanation for this situation is that the surface layer receives heat from the atmosphere, but at the bottom heat loss probably occurs by advection of cold water. During S3 a similar situation as the one observed on S2 happened, although the cooling at 30 m depth is not clear, at 40 m depth heating appears. Since there are no current measurements, it is not certain that this was a cold water intrusion process at this level.

Comparison between the measured SST, from periods S1, S2 and S3, and the climatic SST obtained from the NOAA data, and the observed SST for 1988 (NOAA, 1989), shows the following points: a) observed NOAA 1988 SST had a maximum anticipation of 30 days, b) the SST of S1 (23.41ºC) has a slight phase lag, O (7 days), with the climatic temperature, whereas, with the observed SST the lag was approximately 23 days; c) SST of S2 (26.70ºC) agrees in date with that observed by NOAA, nevertheless this last one is delayed O (25 days) from the climatic, as mentioned; d) SST of S3 (28.33ºC), one week after the passage of hurricane Gilbert, agrees with the climatic, whereas in this part of the year the observed SST remained a month behind.

A synopsis of the behaviour of the observed SST during 1988 (NOAA, 1989), for the quadrant A2, is that by July the profile had a maximum one month lag against the climatic SST profile, and at the beginning and end of the year both curves are in phase.

Analysing the heating speeds, it is conspicuous that the climatic NOAA values, the observed in 1988 by NOAA and the calculated values from the sampling periods do not agree. The two curves, one from 1988 and the climatic one, display two maximums of heating, separated by an upper minimum (“canicula days”). Both patterns are similar, it was noted from the NOAA data for 1988, a gradual increase of heating speed from January through May and a peak of high heating speed between July (0.8ºC d^{-1}), as well as the premature cooling during August (-0.3ºC d^{-1}). By the middle of September hurricane Gilberto ccurred. The calculated heating speeds from the slopes of the series (S1, S2 and S3) came near neither to the observed one nor to the climatic one. This discrepancy could be due to two factors, first it is that the sampling periods were not sufficiently long to represent an average, and the second to the shallow depth of the sampling site that inhibits thermal inertia ($dT/dt \propto h^{-2}$; Jacob *et al*. 2000). From the March (S1) results a strong cooling (-0.12ºC d^{-1}) was observed, this was attributed to the passage of a delayed “North”, whose effect was filtered during the NOAA data processing. During S3, at time of the “canicula”, the heating is high (0.7ºC d^{-1}) with respect to the climatic and observed curves, 0.2 and 0.3ºC d^{-1} respectively.

The heat storage obtained using only the MLD, equation (4), is not satisfactorily approximated and led to non-logical values in S2 and S3. During March (S1) the heat storage was equal to -260 W m^{-2}, with or without parameterization, since there was no thermocline. In S2 and S3 the results were +104 and +39 W m^{-2}, respectively, values that do not represent the thinning of the MLD. That is why for coastal studies, the reservoirs, constituted by the mixed sub-layer and thermocline, must be considered.

The heat storage advective terms for S1 and S2, according to Hernández-Téllez and Aldeco (1990), were -37.4 and -10.8 W m^{-2}, and represented only 10% for S1 and 16% for S2 of the heat storage. Only in the case of a strong current like an anticyclonic ring, the advective term of heat flow is equal to the one of latent heat extraction by hurricane Gilbert (Jacob *et al*. 2000). The competitive effects of stratification and mixing by the wind govern the vertical penetration of the solar heating (Lee and Rudnick, 1996; Sverdrup *et al*. 1942). Still in the presence of strong horizontal variability, Rudnick and Weller (1993) suggest the applicability of a unidirectional model, showing that the heat flow in the surface dominates the integrated heat balance of the upper 40 meters in diurnal and semidiurnal frequencies.

The heat storage during S1 (-260 Wm^{-2}; March) shows a considerable loss of heat, and was attributed to the transit of a severe Northcommonly observed during this period. Hernández-Téllez and Aldeco (1990) used data from the same cruise and computed a flow of 177.4 Wm^{-2} towards the atmosphere (150.6 and 26.8 W m^{-2} of latent and sensible heat, respectively). Levitus (1987) using only SST and a fixed MLD, indicates for the same time in the global Atlantic a value of -110 W m^{-2} (the ocean yields heat). Adem *et al*. (1993), from a numerical model applied to the Gulf of Mexico also with fixed MLD, considered a climatic value of -80 W m^{-2} for January. From here, as noted by Meehl (1984), it is seen that SST is not a good tool for computation of heat storage, especially when entrainment is suspected.

The heat storage during S2 (May-June) was positive (48.5 W m^{-2}), and agrees in phase and value (54-56 W m^{-2}) with that reported by Oort and Vonder Haar (1976) for the study site latitude. Adem *et al*. (1993), from a numerical model applied to the Gulf of Mexico, consider the value of 80 W m^{-2} like climatic for July. Hernández-Téllez and Aldeco (1990) found for S2 a flux of 82.2 W m^{-2} towards the atmosphere (91.1 and -8.9 W m^{-2} of latent and sensible heat, respectively). As can be observed from these values, a heat source must exist, such as radiation, insolation or advection, to support the heat storage (48.5 W m^{-2}) and the latent heat flow towards the atmosphere (82.2 W m^{-2}). The sub-layer and the thermocline lost heat, thinning the mixed layer, a process observed in another region by Alexander and Penland (1996) and attributed to entrainment.

During S3 (September-October) the heat storage was negative, near to zero (-3 W m^{-2}). During this period the water column lost heat at the base of the mixed layer. Even so with the heating of the surface layer, the subsurface layer and the thermocline lost heat (process similar to the observed in S2), giving as a result negative heat storage. The surface heat gain can be due to the re-establishment of the temperature after the cooling caused by the transit of hurricane Gilbert (Jacob *et al*. 2000, Stramma and Cornillon, 1986). Based on the differences in the SST from September 10th to 17th of 1988, Peabody and Amos (1989) they calculated a negative superficial anomaly of 1°C in the zone of the study, caused by the passage of hurricane Gilbert.

An important contribution of the information here discussed is the observation of the erosion of the mixed layer floor, suggesting a differential flow in both strata, the upper (mixed layer) and lower (bottom layer). Because of the advection of cold bottom water, it could be suspected an upwelled origin.

Here where presented quantitative elements to suppose a different behaviour of the SST during this year. Considering the S2 SST and the phase delay of the NOAA observed SST, both a month of advance with respect to the NOAA climatic. As well as the obtained heating speeds during S1, S2 and S3 and those computed from the SST NOAA observed data, with a cooling a month of advance with respect to the climatic one of September. Also the structure of the hurricane Gilbert, class 5. The year of sampling can be considered as of anomalous behaviour.

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